Dear Editor,

Thank you for your careful consideration of our manuscript entitled “A Multi-Angle and Polarization-Based Retrieval Algorithm for Aerosol Layer Height of Smoke and Dust” (Manuscript ID: egusphere-2026-3503). We sincerely appreciate the constructive comments and suggestions provided by the reviewers during the open discussion phase. These comments have been extremely valuable in improving the scientific quality, clarity, and completeness of our manuscript.

We have carefully addressed all referee comments and made substantial revisions to the manuscript. The major improvements include:

1. Clarified the definition and vertical reference framework of aerosol layer height (ALH), including the physical meaning of the retrieved quantity and its relationship with extinction-weighted aerosol height. The revised manuscript now consistently defines ALH relative to sea level and discusses its implications for comparison with independent observations.
2. Improved the theoretical description of the optimal estimation (OE)-based retrieval framework, including additional explanations of the observation vector, error covariance assumptions, and the treatment of multi-angle polarized measurements. The descriptions of Stokes parameters, degree of linear polarization (DoLP), and related retrieval variables have also been revised for consistency.
3. Expanded the information content analysis by providing a more detailed discussion of the degrees of freedom for signal (DFS), demonstrating the contribution of multi-angle polarization measurements to ALH retrieval and clarifying the optimal number of viewing angles required for stable retrievals.
4. Strengthened the validation analysis using independent active remote sensing observations from EarthCARE/ATLID, with additional quality control procedures and aerosol-type screening to ensure the reliability of the validation dataset.
5. Added sensitivity analyses to quantify the impacts of key input uncertainties, including aerosol optical depth uncertainty, on ALH retrieval performance. These results provide further insight into the robustness and uncertainty characteristics of the proposed algorithm.
6. Improved the description of auxiliary datasets and preprocessing procedures, including cloud screening, data collocation, aerosol optical property assumptions, and the use of AERONET observations for constraining aerosol microphysical properties.
7. Expanded the discussion of algorithm limitations, including assumptions of single-layer aerosol structures and uncertainties associated with complex aerosol types such as dust, providing a more comprehensive assessment of the applicability of the proposed method.

All revisions have been highlighted in the revised manuscript, and a detailed point-by-point response to each referee comment has been provided in the final author comments.

We believe that the revised manuscript has been substantially improved and that it now provides a clearer and more comprehensive contribution to aerosol remote sensing and aerosol layer height retrieval from multi-angle polarimetric satellite observations. We hope that the revised manuscript meets the standards of *Atmospheric Measurement Techniques* and will be considered for further evaluation.

Thank you very much for your time and consideration.

Sincerely,

Yong Xue
(on behalf of all co-authors)

Dear Reviewer,

Thank you so much for taking care of our manuscript and we appreciate the opportunity to revise it with comprehensive comments. We highly appreciate the detailed valuable comments from the referees on our manuscript of "A Multi-Angle and Polarization-Based Retrieval Algorithm for Aerosol Layer Height of Smoke and Dust". The suggestions are quite helpful and we have incorporated them in the revised version of manuscript. And we hope that the reviewers and the editors will be satisfied with our responses to the 'comments' and the revisions for this manuscript. Please find our detailed responses below to all these comments/suggestions.

Yours sincerely,

Yong Xue

General Comments

This manuscript presents an aerosol layer height (ALH) retrieval algorithm based on PACE/HARP2 multi-angle polarimetric observations using an optimal estimation framework. The authors first investigate the information content of multi-angle polarization measurements for ALH retrieval using Degrees of Freedom for Signal (DFS) analysis and subsequently develop an ALH retrieval scheme based on HARP2 observations at 441 nm. The retrieval results are validated against EarthCARE/ATLID lidar observations and further compared with the TROPOMI ALH product.

Overall, the topic is scientifically important and timely. With the advent of next-generation multi-angle polarimetric satellite missions, such as PACE and 3MI, retrieving aerosol vertical structure from multi-angle polarization measurements has become an active and important research area in atmospheric remote sensing. The manuscript is generally well organized, and the results demonstrate that polarization measurements can effectively improve ALH retrieval capability. However, several aspects of the manuscript require further clarification and improvement, particularly regarding the algorithm description, uncertainty characterization, validation strategy, and discussion of the results. In particular, the retrieval framework strongly relies on externally provided AOD products and prescribed aerosol models, while the impacts of these assumptions on the retrieved ALH are not sufficiently discussed. Therefore, I recommend that the manuscript undergoes minor revision before it can be considered for publication.

Response:

We sincerely thank the reviewer for the careful reading and constructive comments. These suggestions are very helpful for improving the clarity and robustness of the manuscript. We have addressed all comments point-by-point as follows.

Major Comments / Suggestions for Improvement

1. Please clarify whether any quality control procedures or filtering criteria were applied to the ATLID lidar observations used for validation. Since ATLID retrieval quality may vary under different atmospheric conditions, it is important to describe how the ATLID

data were screened prior to the intercomparison analysis.

Response:

We thank the reviewer for this important comment. In the revised manuscript, we have added a detailed description of the quality control applied to ATLID observations. Specifically, to ensure the reliability of the ATLID validation dataset, quality control and target-type screening were applied to the EarthCARE Level-2 products. Observations were first filtered using the Quality Status flag (Q_{ALD}), retaining only data with Q_{ALD} values of 0, 1, and 2, corresponding to high-quality retrievals, valid data with increased layer complexity, and cases with minor inconsistencies in layer height relative to the A-TC product, respectively. In addition, aerosol type information from the A-TC product was used to further select relevant aerosol categories. Since this study focuses on absorbing aerosol layers, only Dust, Smoke, Dusty_smoke, and Dusty_aerosol_mix cases were retained. This procedure reduces the influence of non-target aerosol types and improves the robustness of the ALH validation.

2. The collocation strategy among HARP2, TROPOMI, and ATLID observations is not sufficiently described. The manuscript should clearly specify: the maximum spatial collocation distance; the temporal collocation window; the spatial averaging strategy; the quality control criteria applied to each dataset. These details are essential for reproducibility and for properly interpreting the validation results.

Response:

We agree with the reviewer that the collocation strategy is critical for interpretation. In the revised manuscript, we have explicitly added:

Spatial collocation radius: 10 km

Temporal window: within 1 hour

Spatial averaging strategy: mean of pixels within radius

Quality control procedures were applied to both the TROPOMI and ATLID datasets following the recommended product quality flags. For HARP2, this study directly used standard Level 2 retrieval products, which have undergone the mission’s internal calibration and screening processes.

These details have now been added to Section 2 of the revised manuscript to improve reproducibility and clarity.

Revision:

Lines 925-927: During the collocation process, HARP2 and TROPOMI pixels are first spatially matched with the ATLID ground track, and the data are then aggregated within a 10 km × 10 km window to reduce the impact of spatial scale mismatches.

Lines 185-190: The local overpass times of PACE, SNPP, Sentinel-5P, and EarthCARE are approximately 13:00, 13:30, 13:30, and 14:00, respectively. Therefore, the temporal differences among HARP2 observations, TROPOMI ALH products, and ATLID Lidar measurements are generally within about one hour. This relatively short time interval facilitates effective intercomparison and validation between ALH retrievals derived from multi-angle polarimetric observations and those obtained from independent active and passive satellite measurements.

Lines 240-244: In addition, the TROPOMI ALH product provides a continuous Quality Assurance (QA) metric ranging from 0 to 1, where 0 indicates retrieval failure or unreliable results, and 1 indicates fully successful retrieval. To ensure data quality, only pixels with QA≥0.5 are retained for validation in this study, while those with QA<0.5 are considered unreliable and excluded. Furthermore, the ALH product has been cloud-screened using the VIIRS/SNPP Enterprise Cloud Mask (ECM).

Lines 268-278: To ensure the reliability of the ATLID validation dataset, quality control and target-type screening were applied to the EarthCARE Level-2 products. First, observations were filtered based on the Quality Status flag (Q_{ALD}) provided in the Quality Status dataset, retaining only samples with QALD values of 0, 1, and 2. Here, Q_{ALD} = 0 indicates high-quality observations; Q_{ALD} = 1 denotes valid data but with the number of aerosol layers exceeding a configurable threshold; and Q_{ALD} = 2 indicates that the retrieved layer height shows some inconsistency with the A-TC (Target Classification) product, although the data remain valid. In addition, aerosol types were further screened using the A-TC product. Since this study focuses on the vertical structure of absorbing aerosols, only observations classified as Dust, Smoke, Dusty_smoke, and Dusty_aerosol_mix were retained for subsequent statistical analysis. This procedure helps reduce the influence of non-target aerosol types on the ALH validation results.

3. The retrieval algorithm relies on externally supplied VIIRS AOD products. Since AOD is a key parameter governing atmospheric radiative transfer, uncertainties in AOD are expected to propagate into the retrieved ALH. It is suggested that the authors clarify: the sensitivity of ALH retrievals to AOD uncertainties; whether retrieval errors increase

significantly under low-AOD conditions. A simple sensitivity analysis would greatly strengthen the robustness assessment of the proposed method.

Response:

We thank the reviewer for raising this important point. We have now added a sensitivity analysis to quantify the impact of AOD uncertainty on ALH retrieval. The results indicate that ALH retrieval is sensitive to AOD uncertainty, with larger biases under low-AOD conditions.

Revision:

Lines 650-683:

Table 4 Retrieval errors in ALH as a function of the δ_{AOD} for the 0.5 and 1.0 AOD conditions[a] (Unit: km).

Error Source	Uncertainty	Smoke (ALH=5 km)		Dust (ALH=5 km)	
		AOD=0.5	AOD=1.0	AOD=0.5	AOD=1.0
AOD (land)	+(0.03+20%)	−0.30	0.06	−0.41	0.17
	−(0.03+20%)	0.56	0.26	1.29	0.24
AOD (ocean)	+(0.03+5%)	−0.17	0.02	−0.17	0.07
	−(0.03+5%)	0.26	0.09	0.57	0.09

[a]The relative error of ALH in the table is $ALH_{ref} - ALH_{retrival}$, and here $ALH_{ref} = 5\ km$.

To evaluate the impact of AOD uncertainty on ALH retrieval, a sensitivity analysis was conducted within the LUT-based optimal estimation framework. In this experiment, all other input parameters, including viewing geometry, surface reflectance, and aerosol model parameters, were kept unchanged, and only the uncertainty in AOD was considered to examine its propagation into the retrieved ALH. This setup is intended to mimic the effect of AOD product uncertainties in practical satellite-based retrievals.

Specifically, two representative aerosol scenarios, i.e., smoke and dust, were selected, with an ALH of 5 km and AOD values of 0.5 and 1.0 used as baseline conditions. AOD uncertainty was introduced as $\pm(20\%\tau + 0.03)$ over land and $\pm(5\%\tau + 0.03)$ over ocean to represent the typical uncertainty levels of the VIIRS AOD product.

Table 4 summarizes the median ALH retrieval errors (unit: km) induced by AOD uncertainty under baseline AOD values of 0.5 and 1.0, calculated across all viewing geometry nodes in the LUT. The results indicate that AOD uncertainty has a significant impact on ALH retrieval, exhibiting clear nonlinear and asymmetric characteristics. For the smoke scenario, when AOD = 0.5, positive uncertainty propagation leads to an ALH error of −0.30 km, while negative uncertainty propagation increases the error to 0.56 km. When AOD increases to 1.0, the corresponding error range decreases to −0.06 km to 0.26 km. A similar behavior is observed in the dust scenario, where the ALH error under low-AOD conditions (0.5) is significantly larger, reaching up to 1.29 km under negative uncertainty propagation, while it decreases to 0.09–0.24 km when AOD = 1.0. Moreover, the dust scenario exhibits higher sensitivity to AOD uncertainty. Specifically, under AOD = 0.5 with negative AOD uncertainty, the ALH error reaches 1.29 km, which is substantially larger than that in the smoke scenario (0.56 km), indicating a stronger dependence of dust aerosol retrieval on AOD a priori information. This is consistent with the findings of Lee et al (2015).

In addition, a comparison between different surface conditions shows that the ALH error induced by AOD uncertainty is generally smaller over ocean than over land. For example, at AOD = 0.5, the ALH error ranges from −0.17 km to 0.26 km over ocean, compared to −0.41 km to 0.56 km over land.

Overall, the results indicate that the impact of AOD uncertainty on ALH retrieval is most pronounced under low-AOD conditions, and exhibits clear variations across aerosol types and uncertainty settings. This highlights that AOD, as a key a priori input parameter, can significantly affect the stability of ALH retrieval through radiative transfer processes.

4. The authors selected the 441 nm channel for ALH retrieval. Although shorter wavelengths generally exhibit stronger sensitivity to aerosol vertical distribution due to enhanced molecular scattering, it remains unclear why 441 nm was ultimately chosen instead of other available HARP2 wavelengths. It would be beneficial if the authors could provide quantitative evidence supporting this choice, for instance by conducting ALH sensitivity analyses at different wavelengths, comparing DFS across channels, and examining Jacobians with respect to ALH. These analyses would strengthen the justification for selecting the 441 nm channel.

Response:

We thank the reviewer for this valuable comment. In Section 3.3 of the revised manuscript, a quantitative comparison of the ALH degrees of freedom for signal (DFS) at different HARP2 wavelengths has been conducted. As shown in Fig. 1, the information content of ALH retrievals decreases with increasing wavelength, following the order 441 nm > 549 nm > 669 nm > 873 nm. Under identical conditions, the 441 nm band provides the highest DFS. Therefore, the 441 nm channel is selected for the ALH retrieval.

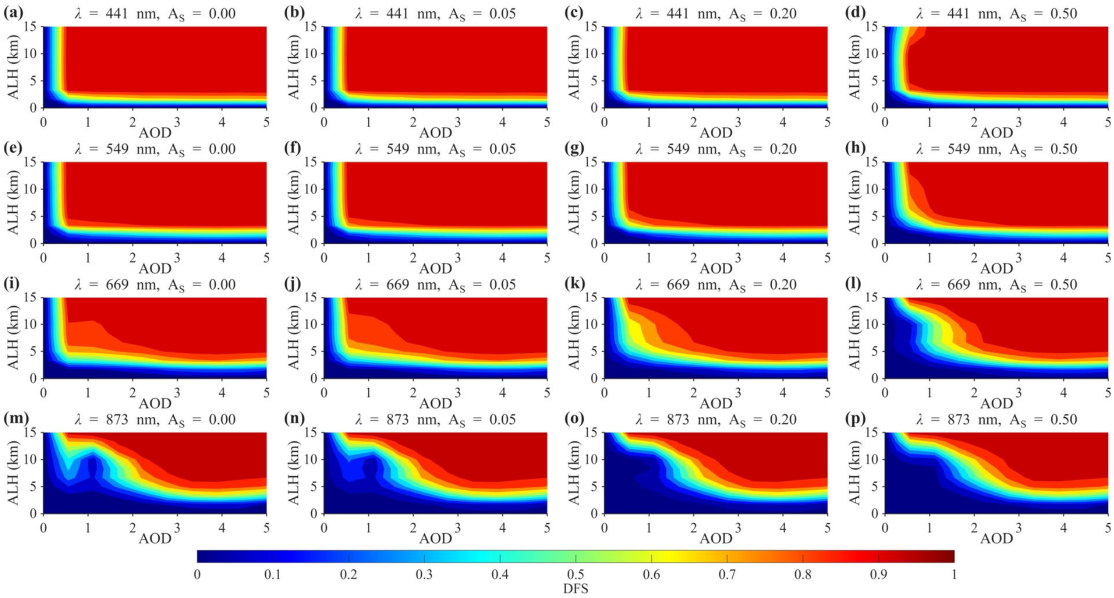

Fig. 1. Characteristics of ALH-AOD-DFS distributions derived from radiance under different spectral bands and surface reflectance conditions. Rows correspond to wavelengths of 441 nm, 549 nm, 669 nm, and 873 nm, respectively, while columns represent different surface reflectance conditions ($A_s = 0.00, 0.05, 0.20, 0.50$). Colors indicate the DFS values of ALH, ranging from 0 to 1.

5. Only six case studies are used for validation in this manuscript. Although these cases appear to be representative, the sample size is relatively limited. Please clarify: the criteria used to select these six cases; whether only favorable observational conditions were considered. In addition, the authors should discuss the extent to which these selected cases are representative of global aerosol conditions.

Response:

We thank the reviewer for pointing out the need to clarify the case selection process. The six cases in this study were not selected based on favorable retrieval results, but were chosen according to several objective criteria. First, these cases correspond to well-documented and widely studied aerosol events, including major biomass burning and dust transport episodes. Second, data availability and quality were a primary constraint; only cases with simultaneous high-quality observations from both HARP2 and TROPOMI on the same day were considered to ensure meaningful intercomparison among sensors. Third, we prioritized scenes with strong aerosol loading (e.g., high AOD and clearly identifiable aerosol plumes) to ensure sufficient signal strength for multi-angle polarimetric retrievals. Fourth, cases with minimal cloud contamination were selected to reduce uncertainties introduced by cloud–aerosol mixing. Finally, spatial continuity and coherence of aerosol plumes were also considered to ensure consistent comparisons across different satellite products.

Revision:

Lines 695-704: The selection of these cases was based on multiple objective criteria rather than retrieval performance. First, all selected events correspond to well-documented and widely studied biomass burning and dust transport episodes. Second, only cases with simultaneous high-quality observations from HARP2 and TROPOMI on the same day were retained to ensure reliable cross-sensor comparison. Third, strong aerosol loading conditions, characterized by elevated AOD and clearly identifiable aerosol plumes in true-color imagery, were prioritized to guarantee sufficient signal strength for multi-angle polarimetric retrieval. Fourth, scenes with minimal cloud contamination were selected to reduce uncertainties associated with cloud–aerosol mixing. Finally, spatially coherent and continuous aerosol plumes within the study region were required to ensure consistency among different satellite retrieval products.

6. The forward simulations in this study assume a single aerosol layer. However, multilayer aerosol structures are frequently observed in real atmospheric conditions, especially during biomass burning and dust transport events, where elevated aerosol layers often coexist with boundary-layer aerosols. It is recommended that the authors clarify: what physical quantity is actually retrieved under multilayer aerosol conditions; whether the retrieved ALH is more representative of an extinction-weighted height, centroid height, or dominant aerosol layer height; the potential biases introduced by multilayer aerosol structures. Furthermore, this limitation should be explicitly discussed in the Conclusions or Discussion section.

Response:

We thank the reviewer for this insightful comment regarding the assumption of a single-layer aerosol structure. We agree that multilayer aerosol conditions are frequently observed in the real atmosphere and may influence the physical interpretation of the retrieved ALH. In response to this comment, we have revised the manuscript to explicitly clarify the physical meaning of the retrieved ALH under multilayer aerosol conditions. Specifically, we now state that, due to the single-layer assumption in the forward model, the retrieved ALH should be interpreted as an extinction-weighted height of the aerosol layers, rather than the height of individual aerosol layers. In addition, we explicitly state in the Conclusions section that the current method has limitations in resolving vertically separated aerosol layers. We also outline possible future directions to address this issue, including the integration of multi-angle stereoscopic information, enhanced polarimetric constraints, and the use of active lidar-derived a priori vertical structure information to improve the capability for characterizing multilayer aerosol structures.

Revision:

Lines 1087-1097: However, it should be noted that the current algorithm is based on a single-layer aerosol assumption. Under multilayer aerosol conditions, the retrieved ALH should be interpreted as an extinction-weighted height of the combined aerosol column, rather than the height of individual aerosol layers. As a result, the method cannot explicitly resolve vertically separated aerosol layers. Future work could address this limitation by incorporating multi-angle stereo parallax information, polarimetric constraints, and a priori vertical structure information from active lidar observations, in order to improve the capability for distinguishing multiple aerosol layers. In addition, further improvements in retrieval robustness and physical consistency may be achieved by refining aerosol optical models, optimizing surface reflectance parameterizations, and integrating multi-source satellite observations within a joint retrieval framework.

7. Additional literature must elaborate on the issue of: (i) aerosol particle size spectra collected at 2.5-min time resolution with a Scanning Mobility Particle Sizer at various height levels. See, for example: https://doi.org/10.1016/j.atmosenv.2012.05.015; (ii) the fact that the aerosol vertical distribution plays a crucial role in shaping the ozone vertical profile and strongly influences the biologically effective radiation that reaches the Earth's surface. See for example: Journal of Geophysical Research: Atmospheres 106.D14 (2001): 14843-14854.

Response:

We appreciate this suggestion. The two recommended references have now been added and discussed in the revised manuscript. They help to further support the importance of aerosol vertical distribution in controlling particle size evolution and radiative impacts on atmospheric chemistry and surface radiation.

Minor Comments / Typographical / Formatting

1. Page 2, line 64: "CALIOP provide" should be "CALIOP provides".

Response:

Corrected as suggested.

2. Suggest clearly and consistently define ALH throughout the manuscript. Different studies may define ALH as extinction-weighted height, aerosol centroid height, or aerosol layer top height. In addition, it should be clearly stated whether all ALH values reported in this study are referenced to mean sea level or to the local surface.

Response:

We thank the reviewer for this valuable suggestion. In the revised manuscript, we have clearly defined ALH. For passive sensors in this study, the retrieved ALH is derived under the assumption of a quasi-Gaussian aerosol vertical distribution and represents the centroid height. For lidar observations, the ALH corresponds to the extinction-weighted height. These two definitions are physically consistent in representing the effective vertical location of the aerosol layer. In addition, we have clarified that all ALH values in this study are referenced to mean sea level.

Revision:

Lines 366-370: The aerosol vertical distribution is assumed to follow a Gaussian-like profile (Spurr and Christi, 2014), defined as:

$$\tau(z) = K \frac{\exp(-\sigma|z - z_{peak}|)}{[1 + \exp(-\sigma|z - z_{peak}|)]^2} \tag{9}$$

where K is related to the column aerosol loading; z_{peak} represents the height of the AOD peak, i.e., the ALH; and σ_t denotes the aerosol layer thickness, which is set to 1.76 km.

Lines 371-378: For quantitative comparison, the ATLID-based aerosol layer height (ALH_{ATLID}) is derived from the Level-2 355 nm extinction coefficient profiles following the method of Koffi et al. (2012), using an extinction-weighted height definition:

$$ALH_{ATLID} = \frac{\sum_{i=1}^{n} \beta_{ext,i} Z_i}{\sum_{i=1}^{n} \beta_{ext,i}} \tag{13}$$

Where $\beta_{ext,i}$ represents the aerosol extinction coefficient (km^{-1}) at altitude Z_i for the i-th vertical layer. The derived ALH_{ATLID} corresponds to the altitude where aerosol extinction is most significant, and its physical meaning is consistent with the quasi-Gaussian vertical distribution assumption adopted in this study (Chen et al., 2021a).

Lines 712-714: All ALH values used in this study—including the TROPOMI ALH product, ATLID-derived ALH calculated using extinction-weighted profiles, and HARP2-retrieved ALH—are defined relative to mean sea level.

3. Suggest carefully check all equations and ensure that every symbol and variable is explicitly defined when first introduced.

Response:

Thank you for your suggestion. We carefully reviewed all equations and ensured that all variables and symbols are now defined upon first appearance in the revised manuscript.

Dear Reviewer,

Thank you so much for taking care of our manuscript and we appreciate the opportunity to revise it with comprehensive comments. We highly appreciate the detailed valuable comments from the referees on our manuscript of "A Multi-Angle and Polarization-Based Retrieval Algorithm for Aerosol Layer Height of Smoke and Dust". The suggestions are quite helpful and we have incorporated them in the revised version of manuscript. And we hope that the reviewers and the editors will be satisfied with our responses to the 'comments' and the revisions for this manuscript. Please find our detailed responses below to all these comments/suggestions.

Yours sincerely,

Yong Xue

This manuscript investigates theoretically the information content of multi-angle polarimetric measurements for ALH retrievals in the UV, using a Degrees of Freedom for Signal (DFS) analysis. It demonstrates that polarisation measurements adds information, especially at geometries that are relevant for satellite observations. Subsequently, an ALH retrieval algorithm is applied to multi-angle polarimetric PACE/HARP2 observations at 441 nm and compared to independent ALH retrievals from EarthCARE/ATLID, using active lidar measurements, and TROPOMI ALH using the O2-A band.

The paper is relevant and interesting, and the analysis is generally of good quality. However, for publication a number of issues need to be addressed, mainly to better explain what has been done and provide concise information.

Response:

We sincerely thank the reviewer for the positive evaluation and constructive comments. Following the reviewer's suggestions, we have carefully revised the manuscript to improve the clarity and consistency of the theoretical description, refine several statements regarding previous studies, provide more detailed descriptions of the simulation settings and figures, and reorganize some theoretical discussions to improve the overall structure of the manuscript.

Revision:

Details are listed below:

l64-67

"Specifically, more photons are scattered back to space at higher altitudes, thereby reducing their probability of penetrating into the lower atmosphere and being absorbed by O_2. As a result, higher aerosol layers lead to stronger Top-of-Atmosphere (TOA) reflectance within the absorption bands."

suggest to reformulate something like:

Specifically, for scattering layers at higher altitudes, the probability for photons to penetrate into the lower atmosphere and be absorbed by O_2 reduces, leading to shallower absorption lines in within the absorption bands for higher altitude aerosol layers.

Response:

We thank the reviewer for this suggestion. We have revised this sentence to better describe the photon transport process and the resulting variation of absorption features in the manuscript.

Lines 93-95: Specifically, for scattering layers at higher altitudes, the probability for photons to penetrate into the lower atmosphere and be absorbed by O_2 reduces, leading to shallower absorption lines in within the absorption bands for higher altitude aerosol layers.

l77

It has shown -> It has been shown

Response:

Thank you for pointing out this grammatical error. We have corrected "It has shown" to "It has been shown" in the revised manuscript.

l107-108

Moreover, the quantitative contributions of multi-dimensional observations to ALH retrieval have not yet been systematically assessed, highlighting the need for further investigation.

I do not agree here. There is a large body in literature, some of which are already ilisted. The GRASP consortium has shown quite systematically that they can use multi-dimensional observation to improve the ALH and other aerosol parameters.

Another reference is

Hasekamp, O. P., P. Litvinov, and A. Butz (2011), Aerosol properties over the ocean from PARASOL multiangle photopolarimetric measurements, J. Geophys. Res., 116, D14204, doi:10.1029/2010JD015469.

Response:

We sincerely thank the reviewer for this important comment. We agree that our original statement was too general and did not sufficiently acknowledge previous studies that have demonstrated the capability of multi-dimensional observations for improving aerosol property retrievals. In particular, GRASP-based retrieval studies and

Hasekamp et al. (2011) have systematically demonstrated that the combination of spectral, angular, and polarimetric measurements can provide additional constraints on aerosol properties, including aerosol vertical information.

Following the reviewer's suggestion, we have revised the related statement in the Introduction to avoid overstatement, added the relevant references, and clarified the specific scientific objective of this study.

Revision:

Lines 145-150: Previous studies, including GRASP-based retrieval frameworks and multi-angle polarimetric retrieval approaches (Hasekamp et al., 2011), have demonstrated the potential of combining spectral, angular, and polarization measurements to improve aerosol property retrievals. Nevertheless, uncertainties remain in quantifying the specific information contribution of individual observation dimensions to ALH retrieval, particularly for multi-angle polarimetric observations under different viewing geometries.

l170

"which further improves the reliability of the data."

This is a rather empty statement. The ALH product is for cloud-screened pixels only. Period.

Response:

We thank the reviewer for this comment. We agree that the original statement was too general. Since the ALH product is already provided only for cloud-screened pixels, describing cloud screening as further improving the reliability of the product is not precise. We have removed the relevant statements from the manuscript.

Section 3.

The theoretical treatment needs improvement. The relationship between eq (1) and (2) is not given. S_epsilon (3) is diagonal, which means that the errors are assumed to be independent, this needs to be mentioned.

The Stokes parameters were mentioned in section 2, but only here treated formally.

Better to remove the introduction in section 2, and treat it here properly. Same for DoLP (change all DOLP to DoLP).

Response:

We thank the reviewer for pointing out that the relationship between Eq. (1) and Eq. (2) was not sufficiently explained in the original manuscript. Eq. (1) describes the nonlinear forward relationship between the atmospheric state vector and the satellite observations. For the DFS analysis, this nonlinear forward model is linearized around a reference state using the Jacobian matrix K, which represents the sensitivity of the simulated observations to the retrieved parameters. Assuming Gaussian distributions for the measurement and forward model errors, the posterior probability density function can be derived within the Bayesian optimal estimation framework by combining the measurement information with the prior constraint. The posterior error covariance matrix is therefore obtained as Eq. (2). We have added this explanation in the revised manuscript to clarify the theoretical connection between the forward model and the retrieval uncertainty formulation.

Second, we have explicitly stated that the measurement error covariance matrix S_ε is assumed to be diagonal, indicating that measurement errors among different observations are considered independent.

Furthermore, we have removed the preliminary introduction of Stokes parameters from Section 2 and provided their formal definitions in Section 3. In addition, all occurrences of “DOLP” have been corrected to the standard notation “DoLP” throughout the manuscript.

Revision:

Lines 300-317: In the framework of optimal estimation theory (Hou et al., 2018), the relationship between the state vector x (containing n parameters) and the observation vector y (with m measurements) can be expressed as:

$$y = F(x) + \in \quad (1)$$

where F is the forward model that describes the physical relationship between satellite observations and atmospheric parameters (such as ALH), x is the state vector to be retrieved, and $\in$ represents the errors arising from forward model simulations and satellite measurements. For the DFS analysis, the nonlinear forward model in Eq. (1) is linearized around a reference state x using the Jacobian matrix $K = \frac{\partial F}{\partial x}$, which represents the sensitivity of the simulated observations to the retrieved parameters. Under the assumption that the measurement and forward model errors follow Gaussian distributions, the posterior probability density function of the retrieved state can be obtained through Bayesian estimation by combining the prior information with the measurement information. The corresponding posterior error covariance matrix S is then expressed as:

$$S^{-1} = K^T S_\varepsilon^{-1} K + S_a^{-1} \tag{2}$$

Where, S_ε denotes the measurement error covariance matrix, and S_a represents the a priori error covariance matrix. In this study, the measurement error covariance matrix S_ε is assumed to be diagonal, indicating that the measurement errors among different observations are independent. It includes uncertainties from both instrument measurements and forward-model simulations.

l244 "radiance III" is unclear.

I also suggest to move eq (13) and its discussion on l632 to section 3. The extinction-weighted height is used in the text before it is defined.

Response:

We thank the reviewer for pointing out these issues.

The expression "radiance III" was a typographical error and has been removes in the revised manuscript.

We also appreciate the reviewer's suggestion regarding the organization of the theoretical framework. We agree that the definition of extinction-weighted height should be introduced before its application in the manuscript. Therefore, Eq. (13) and its related discussion have been moved from the validation section to Section 3, where the theoretical basis and definitions of the retrieval framework are presented. This reorganization improves the logical flow and ensures that the extinction-weighted height is clearly defined before being used in subsequent analyses.

l250 Mie scattering is proper for small and/or spherical particles only.

Table 1: Where are the numbers coming from? The table lists 3 references, the text says Lee et al (2015). Please, be concise and consistent.

Response:

We thank the reviewer for this important comment. We agree that Mie scattering theory is based on the assumption of homogeneous spherical particles and may introduce uncertainties for non-spherical aerosol types, such as mineral dust.

In the revised manuscript, we have clarified that the linearized Mie scattering calculations are performed under the spherical particle assumption for constructing the lookup table. This approximation is generally suitable for fine-mode smoke aerosols, while it may introduce additional uncertainties for dust aerosols due to their non-spherical shapes. This limitation has been added to the manuscript.

Regarding Table 1, we appreciate the reviewer for pointing out the inconsistency in describing the parameter sources. We have revised the text and table to clearly distinguish the origins of different aerosol parameters. Specifically, the aerosol size distribution parameters and fine-mode fraction are adopted from Lee et al. (2015), while the complex refractive indices are taken from Chen et al. (2021b) for smoke and Zeng et al. (2008) for dust.

Revision:

Lines 357-365: These microphysical parameters are specified based on previous studies. The aerosol size distribution and fine-mode fraction (FMF) follow Lee et al. (2015), while the complex refractive indices are adopted from Chen et al. (2021b) for smoke and Zeng et al. (2008) for dust, as summarized in Table 1.

Table 1 Microphysical properties of aerosols in forward modeling

Aerosol Type	Complex Refractive Index	$r_{v1}; r_{v2}$ (μm)	$\sigma_1; \sigma_2$ (μm)	FMF	Reference
Smoke	1.52−0.021i	0.15; 3.25	0.40; 0.75	0.85	(Chen et al., 2021b; Lee et al., 2015)
Dust	1.53−0.008i	0.15; 1.90	0.40; 0.63	0.15	(Lee et al., 2015; Zeng et al., 2008)

l271 MCD43A1 product is a MODIS product, which is not described. Please add.

Response:

We thank the reviewer for pointing out that the description of the MCD43A1 product was insufficient in the original manuscript. We have added a brief introduction of the MODIS MCD43A1 BRDF/Albedo product in the revised manuscript.

Revision:

Lines 221-228: This study incorporates surface bidirectional reflectance information from the MODIS MCD43A1 BRDF/Albedo product (Schaaf and Wang, 2015). Specifically, the BRDF Albedo Parameters dataset was used to characterize the directional surface reflection properties at the corresponding wavelength. The MCD43A1 product provides the three RossThick–LiSparseReciprocal BRDF model parameters, which describe the anisotropic scattering behavior of the land surface (Schaaf et al., 2002). These parameters were used as auxiliary inputs for the radiative transfer simulations to account for surface bidirectional reflectance effects in the aerosol layer height retrieval.

l287

"Under typical aerosol loading conditions (AOD = 0.3–1)"

It is unclear what aerosol type is used in Fig 1 and what the AOD is, since it wavelength-dependent. This should be specified properly and consistently throughout the text. Also see next item.

Fig 1.

The AOD is a wavelength-dependent parameter. In Fig.1 the AOD ranges from 0-5 for all wavelengths, representing markedly different ranges, since the AOD at 441 is 2-3 times higher that at 873 for smoke. It is not clear what is used and the figures should be scaled to the same ranges to be compared as they are in the text now.

Response:

We thank the reviewer for pointing out the ambiguity regarding the aerosol type and the wavelength dependence of AOD in Fig. 1. In this analysis, the aerosol type considered in Fig. 1 is smoke aerosol. Regarding AOD, the values at different wavelengths were converted to the equivalent AOD at 441 nm using the AE to ensure a consistent reference across spectral bands (i.e., AOD_{441} = 0.3–1). The corresponding AOD values at other wavelengths were calculated using the Ångström exponent and used in the radiative transfer simulations. Therefore, the comparisons among different spectral bands are based on consistent aerosol loading conditions. The descriptions in the manuscript and the caption of Fig. 1 have been revised accordingly to explicitly specify the smoke aerosol assumption and the use of AOD_{441}。

Revision:

Lines 403-406: To ensure a physically consistent comparison among different spectral bands, AOD was specified at 441 nm as the reference aerosol loading condition. The corresponding AOD values at other wavelengths were calculated using the AE and used in the radiative transfer simulations (Eck et al., 1999).

Lines 420-425: Fig. 1. Characteristics of ALH-AOD_{441}-DFS distributions derived from radiance under different spectral bands and surface reflectance conditions. The simulations were conducted for smoke aerosols, with AOD_{441} ranging from 0 to 5 as the common reference aerosol loading parameter. For all subplots, the x-axis represents AOD_{441}. Rows correspond to wavelengths of 441 nm, 549 nm, 669 nm, and 873 nm, respectively, while columns represent different surface reflectance conditions ($A_s = 0.00, 0.05, 0.20, 0.50$). Colors indicate the DFS values of ALH, ranging from 0 to 1.

l336

Same as before: aerosol optical depth (AOD = 0.3) is ambiguous. Please, describe exactly how Fig. 2-6 were produced.

Fig. 2-6. The captions should describe what's in the figures: I guess relative azimuth from 0-180 degrees? The axis from 0-10 is unexplained.

Response:

We thank the reviewer for raising this important point. Regarding the ambiguity of aerosol optical depth (AOD), we have addressed this issue in our response to the previous comment and have revised the corresponding descriptions in the manuscript.

Regarding the insufficient descriptions of Fig. 2–6 in the original manuscript. In the revised version, we have clarified the meaning of the coordinates in these figures. Specifically, the radial coordinate (0–10 km) represents aerosol layer height (ALH), while the angular coordinate (0–180°) represents relative azimuth angle (RAA). The figure captions have also been revised accordingly to explicitly describe the coordinate definitions.

Revision:

Lines 484-490: Fig. 2. Comparison of ALH-DFS distributions under different combinations of observational information (*I* vs. *I*+*P*) and surface reflectance conditions. The DFS values were calculated by varying ALH (radial axis: 0–10 km) and RAA (angular axis: 0–180°), while other parameters were fixed at VZA = 0°, SZA = 40°, and AOD = 0.3. The top row shows DFS calculated using radiance (*I*) only, while the bottom row shows DFS obtained by combining radiance and polarization information (*I*+*P*). Columns correspond to different surface reflectance values (A_s = 0.00, 0.05, 0.20, 0.50).

l370

"DFS exhibits a pronounced enhancement with viewing geometry. "

I do not understand this. Viewing geometry in this sense is ambiguous. Please rephrase.

Response:

We thank the reviewer for pointing out this ambiguity. We agree that the term "viewing geometry" was too general and did not clearly indicate which observation parameter was being discussed. In this analysis, the DFS variation mainly corresponds to changes in VZA. Therefore, we have revised the statement by explicitly referring to VZA and clarified the physical mechanism associated with the increased atmospheric path length.

l372-274:

Under large viewing angles, the intensity-only observations are not so bad. I think the conclusion is that for small viewing angles the additional information form polarisation measurements is largest.

Response:

We thank the reviewer for this insightful comment. Following the reviewer's suggestion, we have revised the discussion to clarify that large viewing angles enhance the overall ALH information content, while polarization measurements provide complementary information and achieve the largest additional contribution under small viewing angles.

Revision:

Lines 511-521: In addition, DFS exhibits a strong dependence on VZA. As VZA increases from 0° to 80°, the longer atmospheric scattering path enhances the sensitivity of radiance measurements to aerosol vertical distribution, resulting in increased ALH information content. Under large viewing angles, intensity-only observations already provide considerable information due to the enhanced atmospheric path length. However, the additional contribution from polarization measurements is more pronounced at small viewing angles, where intensity-only observations provide relatively limited constraints on ALH. By incorporating polarization information, the DFS is substantially enhanced under these geometries, demonstrating that polarization measurements provide complementary information beyond radiance observations. Furthermore, under high surface reflectance conditions ($A_s = 0.50$), polarization measurements help maintain higher DFS values by reducing the impact of surface background effects on ALH retrieval.

l428-430: Repetition, move theoretical treatments to section 3.

Response:

We thank the reviewer for this suggestion. Following the reviewer's suggestion, we have moved the relevant theoretical treatments to Section 3, where the theoretical framework and retrieval methodology are introduced. The corresponding discussion in the original section has been removed or revised to avoid redundancy and improve the overall organization of the manuscript.

l475.

The reference Fromm et al from 2010 is a strange reference to describe the transport of a 2025 smoke plume. Please, rephrase. I guess the idea is that this happens more often or happened before.

Response:

We thank the reviewer for pointing out this issue. We agree that the original citation of Fromm et al. (2010) was not appropriately placed, as this reference describes previous wildfire smoke transport events rather than the specific 2025 Canadian wildfire event.

Our intention was to indicate that long-range transport of Canadian wildfire smoke under the influence of prevailing westerly winds and large-scale atmospheric circulation has occurred previously. Therefore, we have revised the sentence to clarify that Fromm et al. (2010) provides an example of similar transport processes rather than evidence for the 2025 event.

Revision:

Lines 731-736: In late May 2025, multiple wildfires occurred in western and central Canada. Under the influence of prevailing westerly winds and large-scale atmospheric circulation, a substantial amount of smoke aerosols was transported to the central and eastern regions of North America, forming a pronounced long-range transport plume. Similar long-range transport of Canadian wildfire smoke driven by large-scale atmospheric circulation has also been reported in previous studies (Fromm et al., 2010).

Dear Reviewer,

Thank you so much for taking care of our manuscript and we appreciate the opportunity to revise it with comprehensive comments. We highly appreciate the detailed valuable comments from the referees on our manuscript of "A Multi-Angle and Polarization-Based Retrieval Algorithm for Aerosol Layer Height of Smoke and Dust". The suggestions are quite helpful and we have incorporated them in the revised version of manuscript. And we hope that the reviewers and the editors will be satisfied with our responses to the 'comments' and the revisions for this manuscript. Please find our detailed responses below to all these comments/suggestions.

Yours sincerely,

Yong Xue

The vertical distribution of aerosols plays significant roles in solar radiation transfer and climate change. The authors use a vector radiative transfer model and information content analysis and evaluate the contributions from key factors, including multiangle and polarimetric information to ALH retrieval. The authors also do some case and sensitivity studies and found that multiangle polarimetric measurements substantially increase the degrees of freedom for signal and improve ALH accuracy. An optimal estimation method is developed. Retrieved ALH values are validated against observations and showed reasonable estimations, such as HARP2 retrievals achieve a root mean square error of 1.03 km. Generally, this manuscript is well organized, written and explained. Some minor comments and suggestions are given.

Response:

We sincerely thank the reviewer for the careful evaluation of our manuscript and for the constructive comments and suggestions. We appreciate the reviewer's positive assessment of our work. Following the reviewer's suggestions, we have revised the manuscript to improve the clarity of the description, strengthen the physical interpretation of the results, and further streamline the presentation. The detailed responses to each comment are provided below.

L143, please explain I, Q, and U.

Response:

Thank you for this suggestion. We have added explanations of the Stokes parameters I, Q, and U at their first appearance in the revised manuscript to improve readability.

Revision:

Lines 199-201: Based on this capability, this study develops a joint retrieval method using multi-angle radiance intensity (*I*) and linear polarization measurements (*Q* and *U*) from HARP2 to improve the sensitivity and accuracy of ALH retrieval.

L145, please rewrite "I represents total radiance intensity ……".

Response:

Thank you for your suggestion. We have moved the sentence to Section 3.1 and rephrased it to provide a more concise and accurate description of the Stokes parameters.

Revision:

Lines 340-344: UNL-VRTM is based on the VLIDORT model (Spurr, 2006) and computes the Stokes vector $[I, Q, U, V]^T$, where I represents radiance, and Q and U denote the linear polarization components (Wang et al., 2014; Xu and Wang, 2019). Circular polarization (Stokes parameter V) is generally negligible in atmospheric studies (Gassó and Knobelspiesse, 2022).

L149-150, "while Q and U denote the linear polarization components that characterize the polarization state of the scattering field" could be removed to L143.

Response:

We appreciate this suggestion. We have moved this description of Q and U to line 143.

L237, "Conversely" could be improved by using another word.

Response:

Thank you for pointing this out. We have replaced "Conversely" with "In contrast" in the revised manuscript to better describe the relationship between the two statements.

L286-287, "the information content of ALH shows a clear decreasing trend with increasing wavelength, i.e., 441 nm > 549 nm > 669 nm > 873 nm", more explanations about the information content of ALH and the mechanism of this sentence are suggested.

Response:

We thank the reviewer for this valuable suggestion. We have added further explanations regarding the physical mechanism responsible for the wavelength dependence of ALH information content. Specifically, the ALH information content is quantified by the DFS, which represents the amount of independent information on ALH provided by the observations. Shorter wavelengths exhibit stronger Rayleigh scattering, resulting in enhanced sensitivity of the top-of-atmosphere radiance to variations in aerosol vertical distribution. In contrast, Rayleigh scattering decreases rapidly with increasing wavelength, leading to reduced sensitivity to aerosol layer height at longer wavelengths. The corresponding explanations have been added to the revised manuscript.

Revision:

Lines 412-416: These results indicate that shorter wavelengths have a clear advantage for ALH retrieval. This behavior is primarily attributed to stronger Rayleigh scattering at shorter wavelengths, which enhances the sensitivity of the radiative field to changes in atmospheric vertical structure. In contrast, Rayleigh scattering weakens at longer wavelengths, leading to a significant reduction in sensitivity to layer height.

L465, "This study selects three representative smoke transport events over North America on May 28, May 30, and June 1, 2025" can be removed and combined to L444-445. Please explain why the selected 3 and 6 events is representative.

Response:

Following the reviewer's suggestion, we have moved the introduction of the selected smoke cases to the beginning of the case study section and removed the redundant description. The subsequent text has been revised to focus on the physical characteristics and representativeness of these cases.

Revision:

Lines 695-704: The selection of these cases was based on multiple objective criteria rather than retrieval performance. First, all selected events correspond to well-documented and widely studied biomass burning and dust transport episodes. Second, only cases with simultaneous high-quality observations from HARP2 and TROPOMI on the same day were retained to ensure reliable cross-sensor comparison. Third, strong aerosol loading conditions, characterized by elevated AOD and clearly identifiable aerosol plumes in true-color imagery, were prioritized to guarantee sufficient signal strength for multi-angle polarimetric retrieval. Fourth, scenes with minimal cloud contamination were selected to reduce uncertainties associated with cloud–aerosol mixing. Finally, spatially coherent and continuous aerosol plumes within the study region were required to ensure consistency among different satellite retrieval products.

6 Conclusion, is a little longer and should be shortened. Please report the key conclusions.

Response:

We appreciate the reviewer's suggestion. The conclusion section has been shortened and revised to focus on the key findings of this study.

Dear Meng,

Thank you very much for your careful handling of our manuscript and for providing us with the opportunity to revise and improve our work. We sincerely appreciate your time, effort, and valuable guidance throughout the review process. We are also grateful to the referees for their thorough and constructive comments on our manuscript entitled "A Multi-Angle and Polarization-Based Retrieval Algorithm for Aerosol Layer Height of Smoke and Dust."

The detailed comments and suggestions from the referees have been extremely helpful in improving the clarity, scientific rigor, and overall quality of the manuscript. We have carefully considered all comments and have incorporated corresponding revisions into the revised manuscript. We hope that the revised manuscript and our point-by-point responses adequately address the concerns raised during the review process and meet your expectations.

Please find our detailed responses to all comments and suggestions below.

Yours sincerely,

Yong Xue

The manuscript by Pei et al. presents a comprehensive analysis of retrieving aerosol layer height (ALH) using observations from NASA's PACE HARP2 instrument. The authors provide a thorough information content analysis of the contributions from spectral, polarization, and angular measurements under different surface brightness conditions and aerosol layer heights. The proposed retrieval algorithm, based on the HARP2 blue band and the full Stokes components (I, Q, and U), demonstrates encouraging performance when compared with TROPOMI and EarthCARE observations. Overall, I found this to be a well-executed and valuable study.

I would also like to draw the authors' attention to the current NASA operational HARP2 aerosol products (FastMAPOL), which include an aerosol layer height (ALH) product derived from HARP2 multi-angle polarimetric observations. These products may be useful for comparison in future studies. The product description is available at https://pace.oceansciences.org/data_table.htm?id=1, and the data can be accessed through the NASA Earthdata Cloud (DOI: https://doi.org/10.5067/PACE/HARP2/L2/MAPOL_OCEAN/3.0). The expected ALH uncertainty is discussed in Gao et al. (2023; https://doi.org/10.5194/amt-16-5863-2023), where the theoretical RMSE is approximately 0.94 km (Figs. 5 and 6), which is very close to the ~1 km validation uncertainty reported in the present study. In addition, this study showed that the ALH uncertainty decreases with increasing aerosol optical depth (Fig. 7), which is also consistent with the findings presented in this manuscript.

Response:

We sincerely thank the reviewer for the careful evaluation of our manuscript and for the constructive suggestions. We greatly appreciate the reviewer’s recognition of the value of this study and the insightful comments regarding the relationship between our retrieval framework and the operational HARP2 aerosol products. Following the reviewer’s suggestions, we have revised the manuscript by adding discussions on the existing HARP2 ALH products, clarifying the differences between our approach and the operational retrieval algorithm, incorporating relevant references, correcting the PACE L1C spatial resolution, and further discussing the retrieval uncertainty in relation to the theoretical uncertainty.

As I can gather here, the algorithm presented in this study differs from the operational algorithm in several aspects, including the selection of one key spectral band, direct use of the I, Q, and U Stokes components, the incorporation of external aerosol information, and the focus of one retrieval parameter rather than a dozen of aerosol microphysics. These design choices appear to simplify the retrieval process while making it more robust to current calibration uncertainties. Based on the reported validation results, the retrieval performance appears reasonable and robust. You may also make this clear.

Response:

We thank the reviewer for highlighting the importance of clarifying the differences between the proposed framework and the operational HARP2 aerosol retrieval algorithm. In the revised manuscript, we have added a discussion in the Introduction to explicitly describe the major design choices of our approach. Specifically, the proposed method focuses on ALH as the primary retrieval parameter rather than simultaneously retrieving multiple aerosol microphysical properties. It utilizes a selected key spectral band (441 nm), directly incorporates multi-angle full linear Stokes components (I, Q, and U), and adopts externally constrained aerosol optical depth information to reduce parameter coupling. These modifications clarify the motivation and advantages of the proposed ALH-focused retrieval strategy.

Revision:

Lines 158-167: Different from existing operational multi-parameter aerosol retrieval algorithms, this study focuses on ALH as the primary retrieval target to avoid strong coupling among multiple aerosol parameters. To enhance the sensitivity of observations to aerosol vertical structure, the proposed framework directly utilizes multi-angle measurements of the full linear Stokes components (I, Q, and U), which preserve polarization orientation information and provide additional constraints on aerosol scattering characteristics compared with approaches based on radiance and DoLP. Furthermore, externally constrained aerosol optical depth information is incorporated to further reduce the dependence of ALH retrieval on simultaneously retrieved aerosol properties, thereby improving retrieval robustness. Based on these analyses, a joint retrieval strategy is developed within an optimal estimation method to achieve robust ALH retrieval over both ocean and land surfaces.

A few more comments below:

Abstract (Line 25), Table 4, and Conclusion (Line 757):

As mentioned above, the reported ALH RMSE of 1.03 km is in excellent agreement with the theoretical HARP2 retrieval uncertainty reported by the PACE team (Gao et al., 2023). This is very encouraging. It would be worthwhile to mention the agreement.

Response:

We thank the reviewer for this valuable suggestion. The comparison between the validation uncertainty obtained in this study and the theoretical HARP2 ALH retrieval uncertainty provides important context for evaluating the retrieval performance. In the revised manuscript, we have added a statement in the Results and Conclusion sections noting that the achieved RMSE of 1.03 km is comparable to the theoretical HARP2 ALH retrieval uncertainty (0.94 km) reported by Gao et al. (2023). This agreement further demonstrates the consistency between the proposed retrieval method and the expected performance of HARP2-based ALH observations.

Revision:

Lines953-958: For all cases combined, the HARP2 retrieval achieves an RMSE of 1.03 km, which is notably lower than that of TROPOMI (1.40 km), with a near-zero mean bias (−0.07 km). The obtained RMSE of 1.03 km is comparable to the theoretical HARP2 ALH retrieval uncertainty (~0.94 km) reported by Gao et al. (2023), indicating good consistency between the validation results of this study and the expected retrieval performance of HARP2-based ALH observations.

Line 56, Line 90, Line 107:

For the polarization-based retrieval approaches, it would be more complete to mention existing HARP2 algorithm and product.

Response:

We have added a brief discussion of the operational HARP2 aerosol products and related retrieval studies in the Introduction section to provide a more complete overview of polarization-based ALH retrieval approaches.

Revision:

Lines 124-130: Meanwhile, polarization observations provide an additional dimension of information for aerosol vertical structure retrieval. Using data from the Research Scanning Polarimeter (RSP), Wu et al. (2016) found that polarization signals in the near-ultraviolet and blue spectral bands exhibit strong sensitivity to ALH. Recently, the NASA operational FastMAPOL product has provided aerosol properties, including ALH, from HARP2 multi-angle polarimetric observations (Gao et al., 2021). These developments demonstrate the potential of multi-angle polarimetric measurements for aerosol characterization.

Line 136:

Xu et al. (2024) is an important reference for ALH retrieval, but it may not be sufficient to describe the HARP2 instrument itself. You may also consider:

Martins, J. V., Fernandez-Borda, R., McBride, B., Remer, L., and Barbosa, H. M. J.: The HARP hyperangular imaging polarimeter and the need for small satellite payloads with high science payoff for Earth science remote sensing, IGARSS 2018, Valencia, Spain, 22–27 July 2018, 6304–6307, https://doi.org/10.1109/IGARSS.2018.8518823.

Response:

Thank you for this suggestion. We have added the recommended reference (Martins et al., 2018) to provide a more comprehensive introduction of the HARP/HARP2 instrument and its capability for multi-angle polarimetric Earth observations.

Line 140:

As mentioned previously, It is interesting to see the retrieval directly using the I, Q, and U Stokes components. The current operational HARP2 Version 3 data still experience some polarimetric calibration challenges. From the operational product, retrievals based only on total intensity and degree of linear polarization (I and DoLP) often exhibit positive AOD biases and large ALH biases. Using the full Stokes vector (I, Q, and U) in this study, which also retains polarization orientation information, may help mitigate some of these calibration-related issues. The use of externally constrained AOD may also improve retrieval robustness by decoupling mutual dependencies between ALH and other aerosol properties.

Response:

We appreciate the reviewer's insightful comment regarding the use of the full Stokes components in the proposed retrieval framework. In the revised manuscript, we have added a discussion of the potential advantages of directly using the linear Stokes components (I, Q, and U) compared with retrieval approaches based on total intensity and DoLP. Specifically, the full Stokes representation preserves polarization orientation information, which provides additional constraints on aerosol scattering characteristics. In addition, we have clarified that externally constrained AOD is incorporated in our retrieval framework to reduce the coupling between ALH and other aerosol parameters, thereby improving retrieval robustness. These modifications have been added to the Introduction section to better explain the motivation and design choices of the proposed approach.

Revisioin:

Lines 151-167: Motivated by the above considerations, the present study aims to enhance information content by extending ALH retrieval from a single spectral dimension to a multi-dimensional observational space that integrates spectral, angular, and polarization measurements.

This approach provides stronger physical constraints for retrieving aerosol vertical structure from passive remote sensing. Through radiative transfer simulations and sensitivity analysis of the Stokes vector, the response of TOA polarized radiance to aerosol vertical distribution and scale height is systematically evaluated. The variation in information contribution under different viewing geometries is further investigated. Different from existing operational multi-parameter aerosol retrieval algorithms, this study focuses on ALH as the primary retrieval target to avoid strong coupling among multiple aerosol parameters. To enhance the sensitivity of observations to aerosol vertical structure, the proposed framework directly utilizes multi-angle measurements of the full linear Stokes components (I, Q, and U), which preserve polarization orientation information and provide additional constraints on aerosol scattering characteristics compared with approaches based on radiance and DoLP. Furthermore, externally constrained aerosol optical depth information is incorporated to further reduce the dependence of ALH retrieval on simultaneously retrieved aerosol properties, thereby improving retrieval robustness. Based on these analyses, a joint retrieval strategy is developed within an optimal estimation method to achieve robust ALH retrieval over both ocean and land surfaces.

Line 144:

Please note that the PACE Level-1C spatial resolution is approximately 5.2 km, rather than 3.5 km.

Response:

Thank you for pointing out this error. We have corrected the spatial resolution of the PACE/HARP2 Level-1C product from 3.5 km to approximately 5.2 km throughout the revised manuscript.

Line 220:

Retrieval uncertainty propagation has also been investigated for HARP2 observations (Gao et al., 2023). That study found that the theoretical ALH uncertainty agrees well with retrieval uncertainties derived from simulations (see Fig. 9). That means the retrieval uncertainty of 1km may also approach to the optimal performance constrainted by measurement uncertainty itself.

Response:

We appreciate the reviewer for pointing out the uncertainty analysis of HARP2 ALH retrieval reported by Gao et al. (2023). In the revised manuscript, we have added a discussion comparing our validation results with the theoretical uncertainty estimated from HARP2 observations. The reported ALH RMSE of approximately 1 km in this study is consistent with the theoretical retrieval uncertainty derived from error propagation analysis in Gao et al. (2023), suggesting that the achieved retrieval accuracy is within the expected uncertainty range of HARP2-based ALH retrievals. The corresponding discussion has been added in the revised manuscript.

Revision:

Lines 953-958: For all cases combined, the HARP2 retrieval achieves an RMSE of 1.03 km, which is notably lower than that of TROPOMI (1.40 km), with a near-zero mean bias (−0.07 km). The obtained RMSE of 1.03 km is comparable to the theoretical HARP2 ALH retrieval uncertainty (~0.94 km) reported by Gao et al. (2023), indicating good consistency between the validation results of this study and the expected retrieval performance of HARP2-based ALH observations.

Dear Yong, thank you for addressing my questions and comments. The revised sections make it clear on the strength of this paper.

Just one more note, in your following revised paragraph, you may like to update one of the references which reflect the ALH retrieval performance from HARP2 (Gao et al 2023, https://doi.org/10.5194/amt-16-5863-2023).

Lines 124-130: Meanwhile, polarization observations provide an additional dimension of information for aerosol vertical structure retrieval. Using data from the Research Scanning Polarimeter (RSP), Wu et al. (2016) found that polarization signals in the near-ultraviolet and blue spectral bands exhibit strong sensitivity to ALH. Recently, the NASA operational FastMAPOL product has provided aerosol properties, including ALH, from HARP2 multi-angle polarimetric observations (Gao et al., 2023). These developments demonstrate the potential of multi-angle polarimetric measurements for aerosol characterization.

Response:

Dear Meng, we thank you for this valuable suggestion. We agree that Gao et al. (2023) represents an important recent advancement in ALH retrieval from HARP2 multi-angle polarimetric observations and should be acknowledged in the Introduction. Following Dr. Gao Meng's recommendation, we have added this reference and revised the relevant paragraph to include the NASA operational FastMAPOL product and its demonstrated capability for retrieving aerosol properties, including ALH, from HARP2 measurements.

The corresponding revision has been made in Lines 124–130 of the revised manuscript.

Dear Ralph,

Thank you so much for taking care of our manuscript and we appreciate the opportunity to revise it with comprehensive comments. We highly appreciate the detailed valuable comments from the referees on our manuscript of "A Multi-Angle and Polarization-Based Retrieval Algorithm for Aerosol Layer Height of Smoke and Dust". The suggestions and notes are quite helpful and we have incorporated them in the revised version of manuscript. And we hope that the reviewers and the editors will be satisfied with our responses to the 'comments' and the revisions for this manuscript. Please find our detailed responses below to all these comments/suggestions.

Yours sincerely,

Yong Xue

A great deal of work has gone into this paper, and I think it is certainly appropriate for publication. I made a few notes, included here, based on our practical as well as our theoretical experience with the MISR multi-angle, radiance-only retrieval algorithm mentioned in the paper, in case they are of use.

Response:

We sincerely thank the Ralph for the positive evaluation of our manuscript and for recognizing the effort invested in this work. We are also very grateful for the insightful notes based on the Ralph's practical and theoretical experience with the MISR multi-angle radiance-only retrieval algorithm. These comments and notes are highly valuable and have helped us further improve the clarity and robustness of the manuscript. We have carefully considered all the suggestions and incorporated the relevant revisions into the revised version.

• The main reference for the MISR MINX algorithm is:
Nelson, D.L., M.J. Garay, R.A. Kahn, and B.A. Dunst, 2013. Stereoscopic Height and Wind Retrievals for Aerosol Plumes with the MISR INteractive eXplorer (MINX). Remote Sens. 5, 4593-4628, doi:10.3390/rs5094593.
This paper contains important points relevant to the current study that are not included in the earlier references cited in the discussion paper.

Response:

We thank the reviewer for pointing out this important reference. We have carefully reviewed the paper by Nelson et al. (2013). Accordingly, we have added this reference and incorporated the relevant discussion in the revised manuscript.

• The vertical resolution of MINX retrievals is between 250 and 500 m, due to the pixel resolution of the MISR imagery and to the geometric nature retrieval algorithm, which does not depend on radiometric calibration uncertainty, AOD uncertainty, or retrieved or assumed particle microphysical properties (relevant to Lines 95-100 in the discussion paper). What is required is su9icient AOD to produce contrast features in the multi-angle imagery of the layer – the rest is geometry. (MISR particle properties are retrieve separate, radiometric retrieval algorithms that do depend on calibration, etc.)

Note that a constraint on AOD magnitude applies to all techniques, including those that apply polarization information. The specific AOD requirements vary among the techniques, and depend on the wavelengths used, viewing and solar geometry, the actual aerosol size distribution and light-absorption properties, and in some cases, surface properties, as you know. (For lidar, aerosol concentration as a function of elevation matters for the backscatter signal.) Note that a wind correction is included in the MINX algorithm, to account for any proper motion of the layer over the time it takes for MISR to acquire images at multiple angles.

Response:

We sincerely thank the reviewer for this valuable clarification regarding the physical basis and performance characteristics of the MISR MINX algorithm. The statements in Lines 95–100 of the original manuscript were not sufficiently rigorous, and we have therefore removed this part in the revised manuscript. In addition, we have revised the discussion of the MISR MINX algorithm to provide a clearer description of its characteristics and advantages.

Revision:

Lines 79-88:

Multi-angle stereo parallax methods estimate aerosol plume height by retrieving the geometric displacement of aerosol features observed from different viewing angles, achieving high vertical resolution (~250–500 m). The retrieved plume height is primarily constrained by geometric information and is therefore independent of radiometric calibration uncertainty, AOD retrieval uncertainty, and aerosol microphysical assumptions. The algorithm also incorporates wind correction to account for plume displacement during the multi-angle acquisition period. The MISR INteractive eXplorer (MINX) software system, developed by the NASA Jet Propulsion Laboratory (JPL) team based on MISR multi-angle observations, has been successfully applied to the height retrieval of wildfire smoke plumes, volcanic ash, and dust aerosols.(Diner et al., 2008; Nelson et al., 2013, 2008).

• MINX keys on the layer of maximum spatial contrast in the multi-angle images. As such, the results tend to skew lower than the highest elevations reported by the CALIPSO lidar, but higher than the infrared spectral methods that typically sample deeper into and even below the aerosol layer (e.g., IEEE Geosci. Remt. Sens. Lett. 2020, doi:10.1109/LGRS.2019.2936332); the UV height retrievals (e.g., TropOMI) can be higher or lower relative to other techniques, depending on several factors, as you know. A point made in several papers (e.g., J. Volcanology and Geothermal Research 2017, doi: /10.1016/j.jvolgeores.2017.03.010, Figure 2 and associated text) is that these techniques ***can yield different layer-height results and still all be correct***, as they are sensitive to different aspects of the aerosol layer.

Response:

We sincerely thank the reviewer for this insightful comment regarding the interpretation of ALH differences among different retrieval techniques. We agree that aerosol layer height retrieved from different satellite sensors and algorithms may represent different physical characteristics of the aerosol layer rather than exactly the same quantity.

Therefore, differences among these retrieval products do not necessarily indicate retrieval errors, as each technique provides information related to different aspects of aerosol vertical structure. We have added additional discussion in the revised manuscript to emphasize that ALH comparisons should consider the underlying retrieval principles and physical definitions of each method.

• On theoretical ground, one would expect the addition of polarization to the multi-angle data in the new algorithm to increase sensitivity to single-scattering (relative to multiple-scattering) and to smaller particles, other factors being equal. So, looking at Figs. 2-6, I'm wondering in a bit more detail than discussed in the current manuscript how results using this algorithm when polarization is included difer from those for the same algorithm and layers when only the multi-angle data are used. Understandably, the biggest differences tend to appear when the surface albedo is 0.5, especially when the AOD is just 0.3 (and I think you are assuming fine-mode particles).

One thing I could not find is the view-angle range for HARP-2. The 80˚ VZA is quite steep; for MISR the VZA range is nadir to ±70.5˚, and from our sensitivity studies, the range of VZAs sampled is one of the leading factors in determining layer-height sensitivity, more important for geometric height-retrieval applications than the number of view angles, once at least 4 or 5 well-spaced view angles are available. (This also shows up in your Fig. 7.) At the steepest view angles, however, atmospheric refraction, surface texture and shadowing, and other factors become increasing issues. In our experience, another factor of practical relevance is pixel resolution, which sets a limit on height resolution for geometric retrievals. For HARP-2, the pixel-resolution is 2.5

km at nadir and varies with view angle (you use the 3.5 km pixel product), vs. 275 m at nadir in all channels and at all angles in the red band for MISR; full resolution is used in the MINX retrieval for this reason.

Response:

We thank the reviewer for this insightful comment. We agree that a more detailed explanation of the differences between the multi-angle radiance-only configuration and the combined multi-angle polarization configuration is needed. In the revised manuscript, we have expanded the discussion associated with Figs. 2–6 to clarify the physical mechanisms underlying the observed increase in DFS when polarization is included. Specifically, we explain that polarization measurements are primarily sensitive to single-scattering processes and are less affected by surface reflection compared to radiance measurements. As a result, polarization provides additional independent constraints on aerosol scattering geometry and vertical distribution. We further clarify that the DFS enhancement is most significant under conditions of high surface albedo and low aerosol optical depth, where radiance-only observations are strongly influenced by surface reflection and thus exhibit reduced sensitivity to aerosol vertical structure.

Regarding viewing angles, we have added information about the HARP2 instrument's viewing angles to the revised manuscript. Specifically, at the 441 nm wavelength used in this study, HARP2 provides 10 discrete viewing directions with nominal viewing angles ranging from approximately −55.9° to 53.8°. Here, the VZA range from 0° to 80° used in the DFS analysis was intended as a theoretical sensitivity experiment to investigate how the information content of ALH retrieval changes with observation geometry. In the actual ALH retrieval experiments, the observation geometry is fully determined by the HARP2 Level-1 product. Specifically, the pixel-level sensor zenith angle and relative azimuth angle provided by the geolocation data are directly used in the radiative transfer simulations and retrieval process. Therefore, the retrieval results are based on the actual HARP2 viewing geometry rather than the idealized VZA range used in the sensitivity analysis.

Regarding the pixel resolution, it directly limits the achievable vertical accuracy of geometric-based retrieval approaches. We previously considered applying the stereoscopic height approach used by MISR to HARP2 observations for ALH retrieval. However, due to the relatively coarse spatial resolution of HARP2 (approximately 3.5

km), the height retrieval uncertainty from a purely geometric approach was found to be relatively large. Therefore, in this study, we adopted a radiative transfer model-based approach to retrieve ALH, in which the multi-angle observations provide additional radiometric constraints and enhance the sensitivity to aerosol vertical distribution.

Revision:

Lines 500-548:

Under the same retrieval framework and identical aerosol layer conditions, the difference in information content between multi-angle observations and multi-angle polarimetric observations primarily arises from their different sensitivities to various scattering components involved in the radiative transfer process. Multi-angle radiance measurements primarily characterize the integrated radiative response of the coupled atmosphere–surface system, where the observed signal generally consists of contributions from surface reflection, aerosol single scattering, and multiple scattering processes. Under conditions of low AOD or high surface albedo, the surface-reflected component can become a dominant contributor to the measured radiance, while multiple scattering can obscure the signatures associated with single-scattering processes. Consequently, when only multi-angle radiance observations are used, the impact of ALH on the observed signal is mainly manifested through indirect modulation of radiative path length and scattering geometry. The resulting ALH sensitivity is relatively weak and can be strongly coupled with other parameters, such as AOD and surface reflectance, leading to a more ill-posed inverse problem (Dubovik et al., 2011).

In contrast, incorporating polarization information extends the measurement vector from radiance-only observations to a combined set of radiance and polarization states, thereby fundamentally altering the sensitivity structure of the observations to aerosol scattering processes. A key feature of polarized radiance is its enhanced sensitivity to single-scattering processes, whereas multiple scattering tends to reduce polarization through depolarization effects. Meanwhile, surface reflection generally contributes much less to polarized signals than to total radiance, particularly for rough or approximately isotropic surfaces. Therefore, polarization measurements can substantially reduce the influence of surface background and multiple-scattering contributions, providing a more direct constraint on aerosol scattering geometry and particle microphysical properties.

Under these conditions, the impact of ALH on polarization signals is primarily associated with changes in the scattering-angle distribution and the corresponding photon path geometry of single-scattering processes, resulting in enhanced physical sensitivity to aerosol vertical distribution. In addition, polarization measurements are more sensitive to the scattering characteristics of small-sized aerosol particles, such as fine-mode smoke aerosols, because particle-scale scattering processes produce stronger polarization responses. This further improves the detectability of variations in aerosol vertical structure. Within the optimal estimation framework, the inclusion of polarization information effectively expands the dimension of the observation vector, transforming the Jacobian matrix from one based solely on radiance sensitivity into a combined sensitivity matrix containing both radiance and polarization information. Since radiance and polarization observations exhibit different response patterns to aerosol and surface parameters, particularly with respect to the sensitivity relationships among ALH, AOD, and surface reflectance, the combined Jacobian matrix becomes less correlated, leading to improved parameter separability and increased DFS

(Mishchenko et al., 2007). This enhancement is particularly pronounced under conditions where parameter coupling is strongest, such as high surface albedo (0.5) and low AOD (0.3). Under these conditions, radiance measurements are strongly influenced by surface contributions, whereas polarization measurements retain stronger sensitivity to atmospheric scattering, resulting in enhanced complementarity between the two observation types.

Overall, the incorporation of polarization information into multi-angle observations is not simply an increase in the number of measurements, but rather the introduction of an additional independent information dimension that is more sensitive to single-scattering processes and less sensitive by surface reflection. By reducing the coupling among aerosol and surface parameters, polarization observations improve the physical constraint on ALH retrieval. Consequently, the overall sensitivity to ALH is enhanced, while the dependence of retrieval performance on specific viewing geometries and surface conditions is reduced, enabling more robust ALH retrievals over a broader range of surface types and observation geometries.

Dear Ralph,

Thank you very much for your careful review of our manuscript and for providing valuable comments and suggestions that have helped us improve the quality and clarity of our work. We sincerely appreciate your time, effort, and insightful guidance throughout the review process.

The detailed and constructive comments have been extremely helpful in strengthening the scientific presentation and improving the overall quality of the manuscript. We have carefully considered all of your suggestions and have incorporated corresponding revisions into the revised manuscript. We hope that the revised manuscript and our point-by-point responses adequately address your comments and concerns.

Please find our detailed responses to each comment below.

Yours sincerely,

Yong Xue

Thank you for considering my suggestions, Yong. This is important work. After reading over your notes, I have a couple of additional thoughts, in case they are of use:

I think it might be worth emphasizing the point you make about using intensity and polarization in the ALH retrieval, rather than a purely geometric approach, because the HARP-2 pixel resolution is relatively coarse. This contrasts with MISR, which lacks polarization, but includes steeper view angles and has higher pixel resolution.

Response:

We appreciate Ralph for highlighting the importance of clarifying the distinction between the proposed HARP2-based ALH retrieval approach and purely geometric retrieval methods. Following the reviewer's suggestion, we have added a discussion in the revised manuscript to emphasize that HARP2 and MISR represent complementary approaches for ALH retrieval. MISR primarily utilizes high spatial resolution and large angular diversity to identify aerosol-layer geometric contrast features, whereas HARP2 provides an additional polarization dimension that enhances constraints on aerosol scattering properties and vertical structure, despite its relatively coarser spatial resolution.

A surface contribution, due to some combination of low AOD and bright surface, can limit our ability to perform an ALH geometric retrieval at all with MISR. But unlike radiance retrievals, this does not really contaminate the retrieval, because we can perform an ALH retrieval only if we can see contrast features at multiple angles in the aerosol layer itself. The steeper-angle views enhance the aerosol-layer contribution relative to the surface contribution, which helps improve aerosol-layer contrast-feature visibility. As such, the 60° and 70° view angles make important contributions to the MISR ALH retrievals.

Response:

We appreciate Ralph for providing this additional explanation of the physical mechanism underlying MISR geometric ALH retrievals. Exactly, the contribution from surface reflectance and aerosol loading conditions plays an important role in determining the applicability of geometric retrieval approaches. In MISR retrievals, sufficient aerosol-layer contrast features observed from multiple viewing angles are essential for successful ALH retrieval, and the enhanced aerosol-layer contribution at large viewing angles provides important constraints by increasing the visibility of these contrast features.

Following the suggestion, we have added a discussion in the revised manuscript to clarify that MISR and HARP2 rely on different but complementary physical constraints for ALH retrieval. While MISR benefits from high spatial resolution and large angular diversity to exploit geometric contrast features, the HARP2-based approach developed in this study constrains ALH through radiative transfer modeling of multi-angle radiance and polarization signals. The additional polarization information provides complementary sensitivity to aerosol vertical structure, particularly under conditions where geometric contrast features may be limited.

With MISR, we perform the ALH retrievals with each of the red and blue spectral bands. The red band is reported at ~250 m at all nine view angles, so if the aerosol is sufficiently visible in this band, the red retrieval provides results with the highest vertical resolution. However, the AOD is generally greater in the blue band, especially when small smoke or pollution particles dominate, and in such cases, the blue channel, reported at 1.1 km at all MISR angles except nadir, sometimes offers greater sensitivity.

Response:

We thank Ralph for providing this additional clarification regarding the roles of different spectral bands in MISR ALH retrievals. The complementary characteristics of the red and blue channels, including the higher spatial resolution of the red band and the enhanced aerosol sensitivity of the blue band under conditions dominated by fine-mode aerosols, provide important constraints for geometric ALH retrievals.